ELEVATED TEMPERATURE CRACK GROWTH

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ABSTRACT

The problem of crack growth in hot path components such as combustor liners is complicated by several practical and theoretical considerations. The loading environment of such components involves high temperature levels and gradients that lead to considerations such as thermal stresses, crack closure, hold time, inelastic strains - both time dependent and independent, and Thermal Mechanical Fatigue (TMF). In general, a good understanding of the influence of these factors on crack growth has not been obtained. At the same time, several nonlinear fracture mechanics parameters have been suggested for such applications; however, most of the proposed methods have not been tested for broad applications such as required for hot section components. It was the purpose of this program to evaluate proposed nonlinear methods by performing a thorough experimental and analytical study. The results illustrated that much progress has been made in developing nonlinear methods. This work was performed on contract NAS3-23940 with the NASA-Lewis Research Center.

EXECUTIVE OVERVIEW OF: ELEVATED TEMPERATURE CRACK GROWTH

The development of suitable predictive methods for high temperature inelastic crack growth involved several technology considerations. The important factors were an outgrowth of the hot path problems, but there were several factors that called for technology assessments and development. These latter factors included selection of a lower temperature alloy to simplify the experimental work; development of detailed, but proper, experimental methods; selection of appropriate parameters from a long list of nonlinear Path-Independent fracture mechanics integrals; and correlation of experimentally measured crack growth through detailed finite element simulations of the tests to calculate the nonlinear Path-Independent integrals.

- Alloy selection
- Experimental considerations
  - Specimen development
  - Closure measurement
  - Temperature gradients and cycling
- Nonlinear fracture mechanics
  - Numerous path-independent integrals
  - Detailed review
  - FEM post-processor
  - Initial evaluation
- Experimental simulations
  - Crack release
  - Measured boundary conditions
  - PI integral correlation

Figure 1. Technology Considerations

EXECUTIVE OVERVIEW OF: ELEVATED TEMPERATURE CRACK GROWTH

The results of the current program strongly suggest that significant progress has been made in the development of nonlinear fracture mechanics for application to problems of importance to hot section components of gas turbine engines. This conclusion is based on a thorough analytical and experimental evaluation of crack growth in the nonlinear regime. There, nevertheless, remain areas of developmental activities such as thermo mechanical fatigue, thermal gradients, and time dependence.

- Developed new specimen geometry
- Path-independent integrals are available for hot part applications
- Extensive data base collected
- Excellent isothermal data correlation obtained at 538C
- TMF data tended to agree with max stress isothermal data
- Additional work:
  - TMF, thermal gradient, and time dependence
  - Crack closure
  - Geometry verification
  - Numerical improvements

Figure 2. Program Results and Conclusions

SPECIMEN DESIGN AND MEASUREMENTS

The attached figure shows a schematic of the gage section of the buttonhead single edge notch specimen that was developed during this program. Shown in the figure are the locations of the three extensometers and the potential drop leads (for monitoring crack length). The control extensometer was used to simulate strain control, and its value was controlled to vary in a specified way throughout an experiment. The CMOD gage was used to measure the occurrence of crack opening and closure. The back surface extensometer was used with the control extensometer to help establish the boundary conditions in the FEM analyses. The specimen met often conflicting goals of the program, and proved to be easy to analyze via FEM by using the extensometer measurements for boundary conditions.

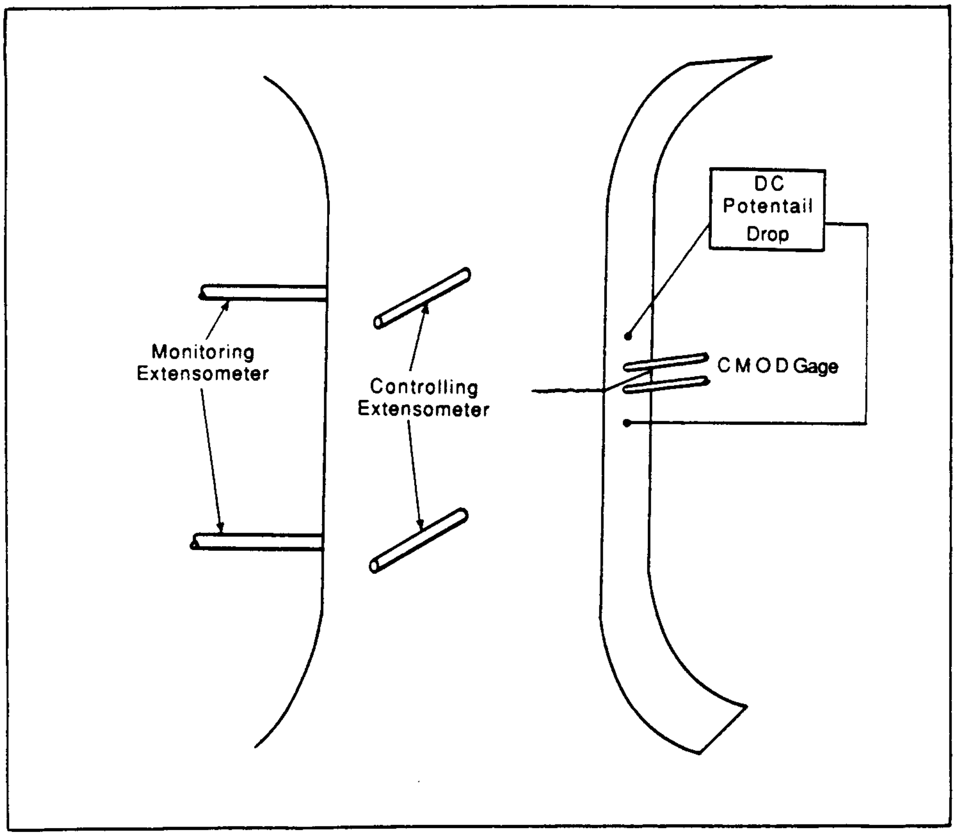

Figure 3. Schematic Drawing of SEN Test Method

LIMITATIONS OF LINEAR ELASTIC FRACTURE MECHANICS

Using the SEN specimen, crack growth properties were measured for a variety of conditions of interest to hot section components. One basic property is the effect of inelastic strain on crack growth rate. As shown in the figure, increasing strain range increases the measured crack growth rate, even though a linear elastic fracture mechanics parameter, the stress intensity factor, is used. This result shows that the effect of inelastic strains is to make predictions based on elastic fracture mechanics potentially nonconservative. It was for this reason that the various nonlinear PI integrals were developed, and it was a purpose of this contract to determine which approach would provide the best method for analyzing such conditions.

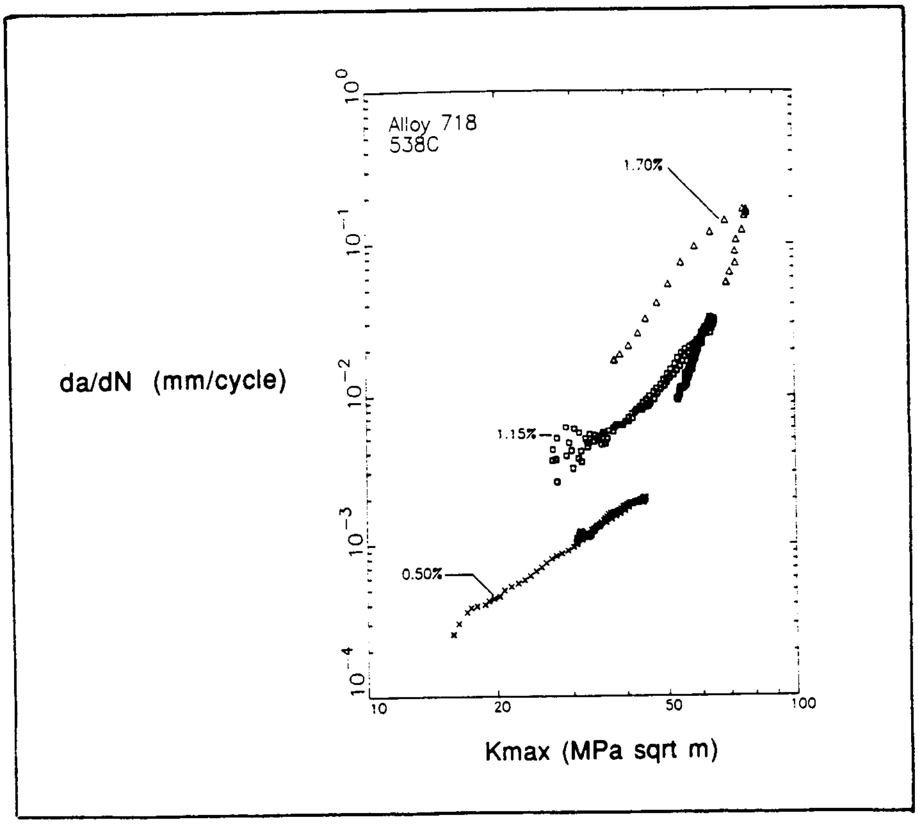

Figure 4. Limitation of Linear Elastic Fracture Mechanics

PROPOSED PATH INDEPENDENT INTEGRALS

A critical element in the program was to evaluate proposed nolinear fracture mechanics parameters which are Path Independent integrals. The attached figure shows several proposed methods. For a given application the easiest way to calculate the value of the parameter is to perform a FEM analysis, and then use a post processor to evaluate the integral; this was the approach used in this program. A finite element post processor was written to calculate the PI integrals for conditions of interest to hot section components.

<u>Rice's J-Integral</u>

$$J = \int_\Gamma (n_1 W - t_i u_{i,1}) ds$$

where $W = \int_0^{\varepsilon_{ij}} \sigma_{ij} \, d\varepsilon_{ij}$

<u>Wilson and Yu's Thermoelastic Integral</u>

$$J_W = \int_\Gamma (n_1 W - t_i u_{i,1}) ds - \alpha(3\lambda + 2\mu) \int_A [\tfrac{1}{2}(\theta \varepsilon_{ii})_{,1} - \varepsilon_{ii} \theta_{,1}] dA$$

Where

$$W = \tfrac{1}{2} \sigma_{ij} \varepsilon_{ij}$$

<u>Gurtin's Thermoelastic Integral</u>

$$J_G = \int \left| n_1 W - t_k u_{k,1} - \frac{\alpha^2 (3\lambda+2\mu)^2}{2(\lambda+\mu)} \theta^2 n_1 + \frac{\alpha\mu(3\lambda+2\mu)}{(\lambda+\mu)} \left(\theta \frac{\partial u_1}{\partial n} - u_1 \frac{\partial \theta}{\partial n}\right) \right| ds$$

Where

$$\frac{\partial}{\partial n} = n_j \frac{\partial}{\partial x_j}$$

and

$$W = \mu \, \varepsilon_{ij} + \frac{\lambda}{2} (\varepsilon_{kk})^2$$

<u>The J_θ-Integral by Ainsworth et al.</u>

$$J_\theta = \int_\Gamma (n_1 W - t_i u_{i,1}) ds + \int_A \sigma_{ij} \varepsilon_{ij,1} dA$$

where

$$W(\varepsilon'_{ij}) = \int_0^{\varepsilon'_{ij}} \sigma_{ij} d'_{ij}, \text{ and } \varepsilon'_{ij} = \varepsilon_{ij} - \varepsilon^\theta_{ij}$$

Figure 5. Proposed Path Independent Integrals

FEM MESH AND BOUNDARY CONDITIONS

To do a FEM analysis, it is, of course, necessary to develop a mesh of the specimen that is being studied. The attached figure shows the mesh of the buttonhead SEN specimen that was used in the simulation of the experimental results. The plane stress model consisted of 421 nodes and 688 constant strain triangular shaped elements. There were also 33 gap elements located along the plane of symmetry where the crack was assumed to be propagating. The gap elements allowed the model to simulate the effect of crack opening and closure. Along the top half of the model the measured displacements were used as displacement boundary conditions, so that an exact geometric model of the specimen was not needed. A large effort including three dimensional analyses was made to verify that this analysis method was accurate.

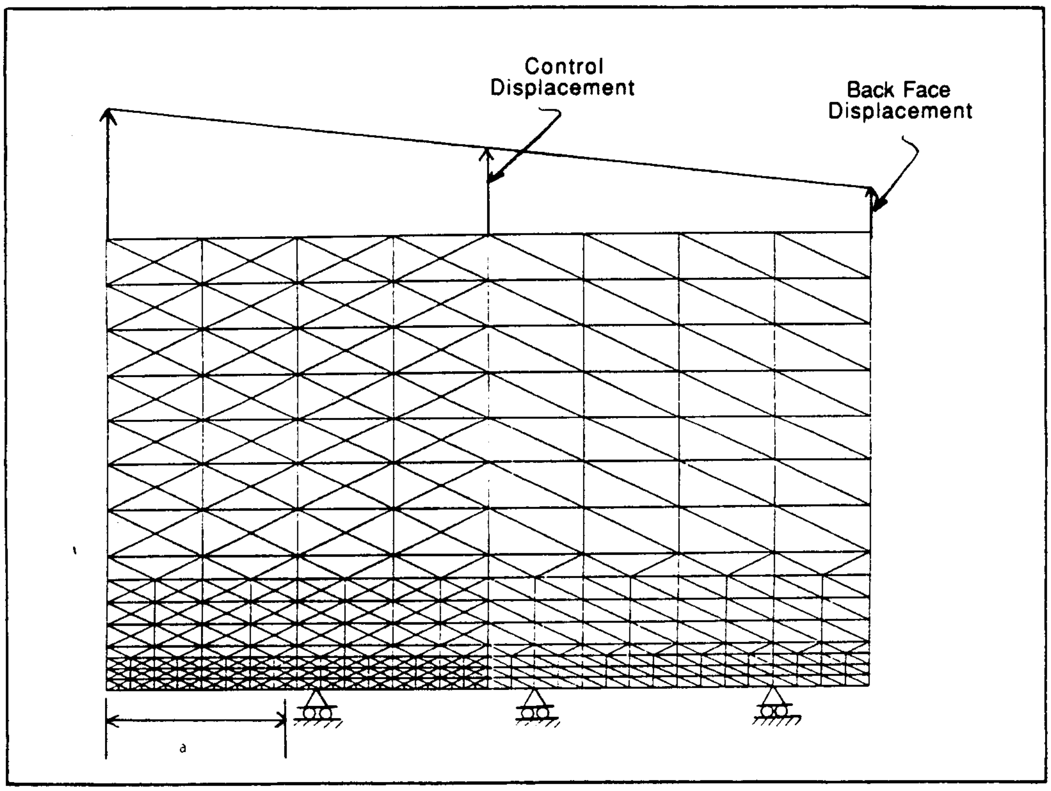

Figure 6. Finite Element Model of the Gage Section of Single Edge Notch Specimen

ANALYTICAL SIMULATION OF CRACK GROWTH

Besides understanding the boundary conditions, it is also necessary to simulate the influence of crack closure in the FEM analysis, to correctly calculate the value of the fracture mechanics parameters while the crack is open. To include the closure effect, it is necessary to simulate the plastic wake that is created by a growing crack. The attached figure schematically shows how the crack was incremented in the analyses. After a complete loading cycle, simulated by the control displacement going through a complete cycle, the crack is incremented over the length of a couple of element widths. Another cycle is then simulated before the crack is incremented again. In this manner, the whole history of the loading sequence can be simulated giving confidence in the resulting PI integrals. It should be noted that this process is inherently nonlinear; thus, the analysis has two nonlinear loops since the material is also nonlinear because of plastic strains.

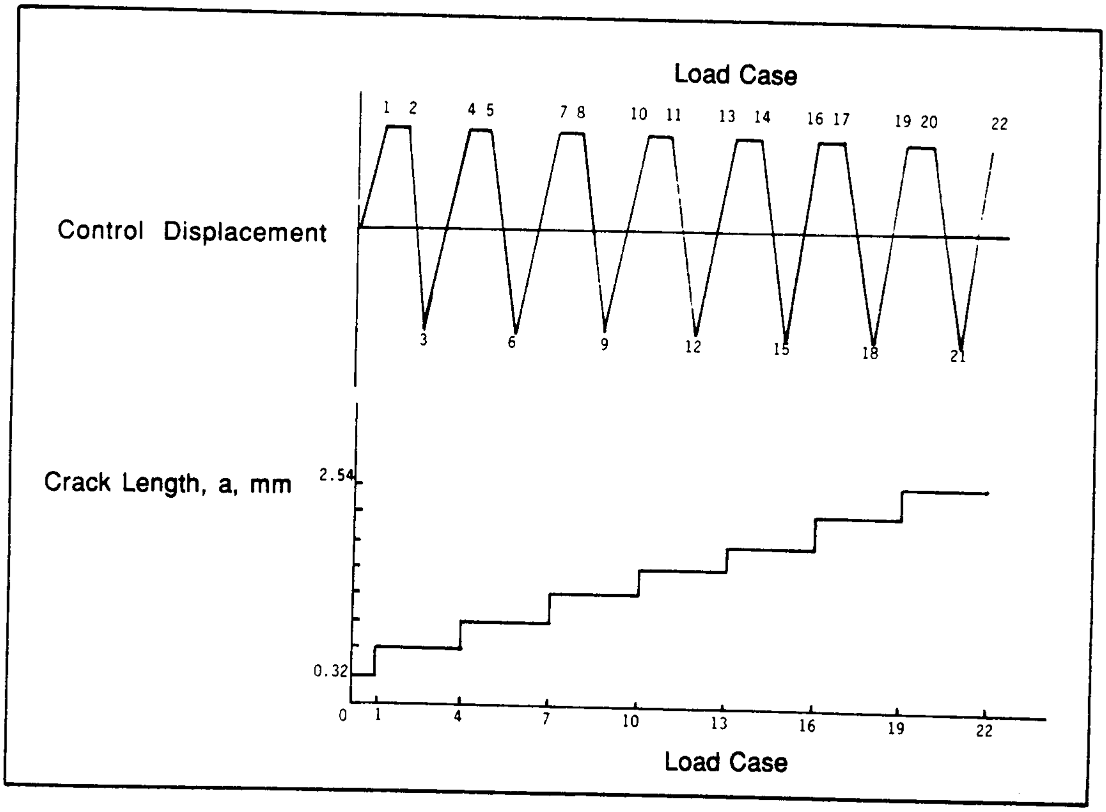

Figure 7. Schematic of Loading Steps in Crack Growth Simulation

CORRELATION OF FEM AND EXPERIMENTAL RESULTS

After each finite element simulation, it is possible to compare the accuracy of the analysis with the experiment. This is accomplished by comparing two test measurements not used in generating the analysis: neither the applied load (or nominal stress) nor the measured crack mouth opening displacment, CMOD, are used in the analytical simulations. The attached figure shows two such comparisons from a single test with a strain range of 1.15% at two different crack lengths. As shown, the analytical procedure very accurately predicts the variation in nominal stress with CMOD for both short and long cracks.

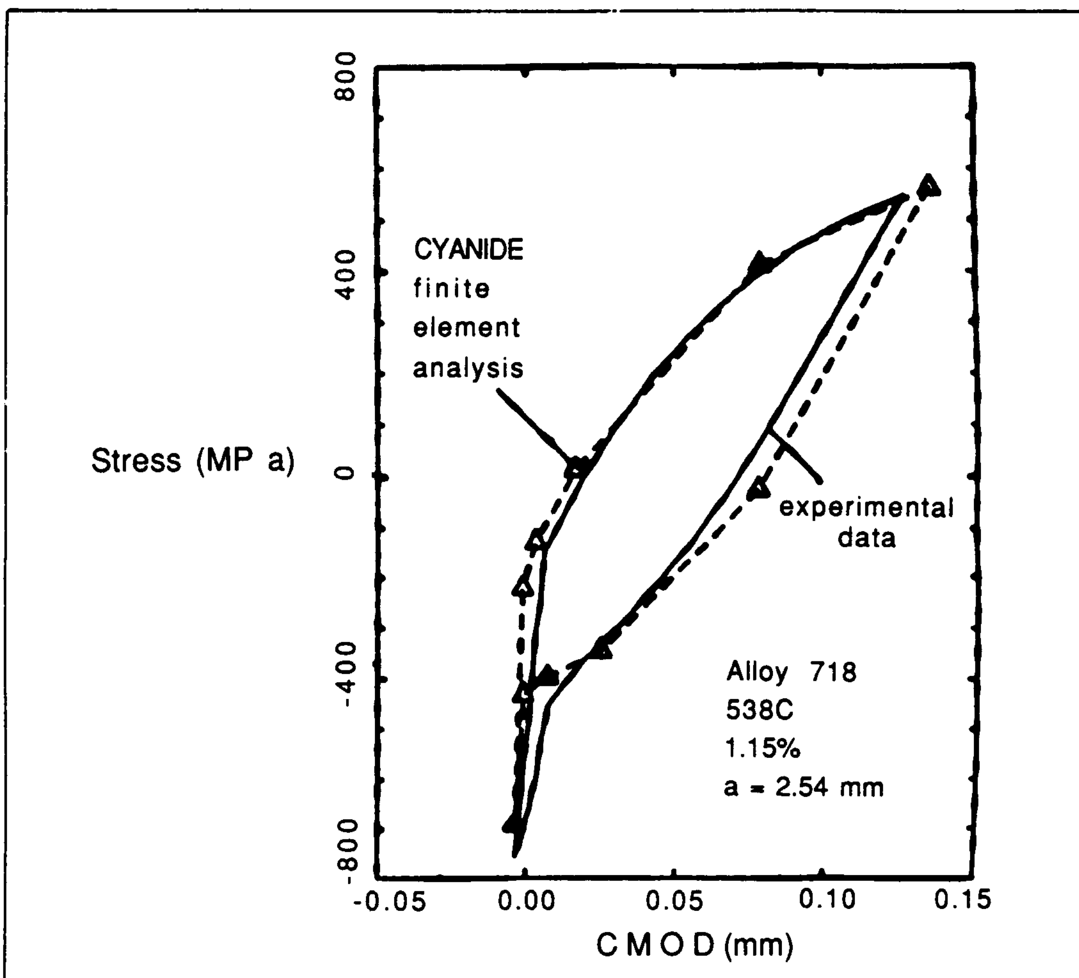

Figure 8. Average Cross Section Stress -CMOD Hysteresis Loop

PATH INDEPENDENCE

Once the analysis has been shown to correlate with the experimental measurements, the results can be used with confidence to calculate the PI integrals. A fundamental property of the nonlinear fracture mechanics integrals is path independence. The attached figure shows that this property was maintained in the current analyses for one of the integrals that was found to be capable of correlating inelastic strain crack growth.

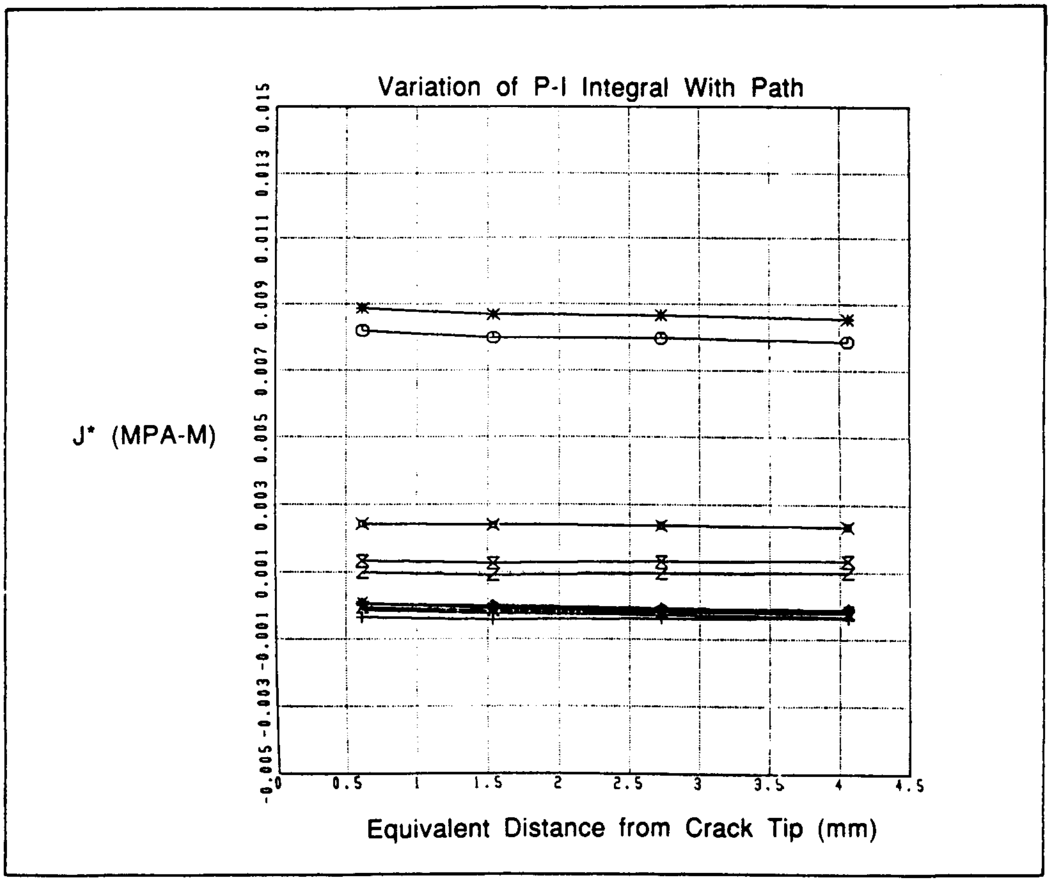

Figure 9. Path Independence

CORRELATION OF CRACK GROWTH DATA

Using the PI integrals and knowing the measured crack growth rates from a given test, it is possible to determine whether a parameter can correlate the measured crack growth rates from several different tests. The attached figure shows that one PI integral can correlate the crack growth rate results at one temperature with different strain ranges. The same test results were shown earlier in a plot which compared the data on the basis of the stress intensity factor. It was found that several nonlinear parameters were capable of correlating these data. With parameters such as these, better predictions of crack growh in hot path components will be possible.

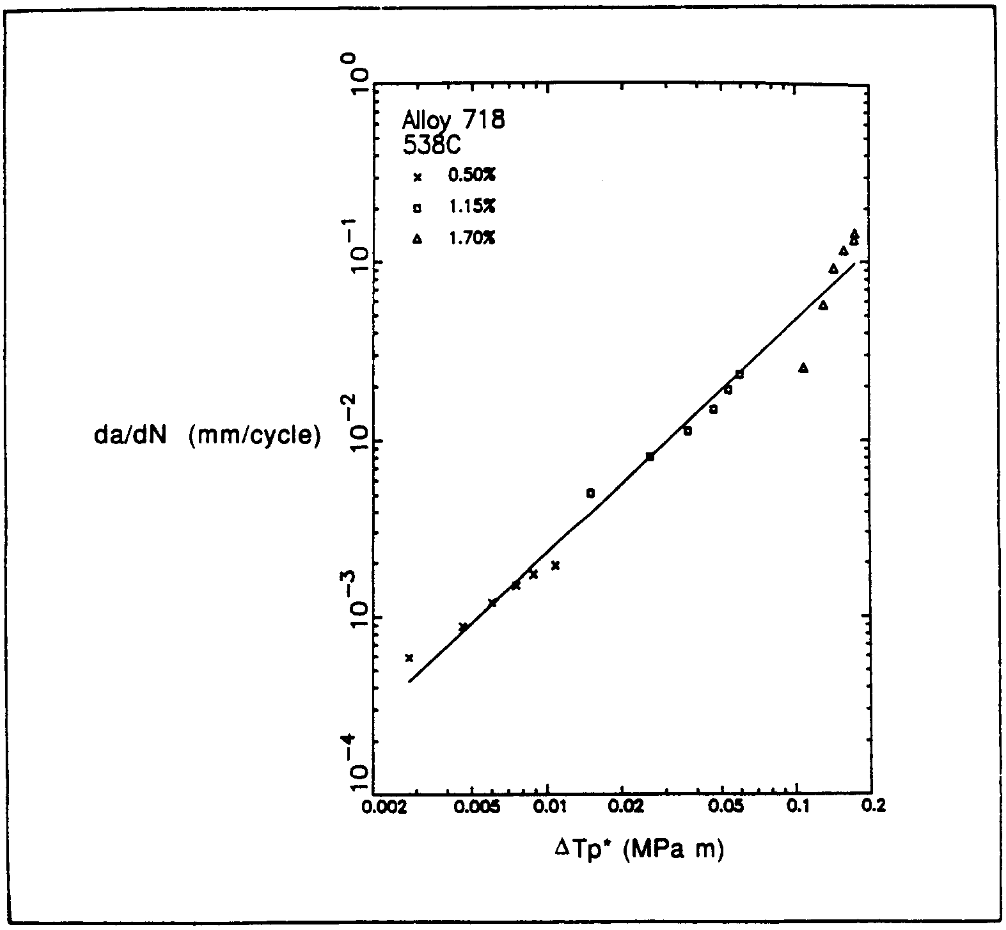

Figure 10. da/dN Versus ΔTp^*

ANALYSIS OF TEMPERATURE GRADIENT EXPERIMENT

Another factor of importance to predicting crack growth in hot path components, is the influence of temperature gradients. The attached figure shows a comparison of predicted load with control displacement for a cracked SEN specimen which was tested with a temperature gradient of over 175C maintained over the gage section. As shown, the response is well predicted using nonlinear FEM analysis.

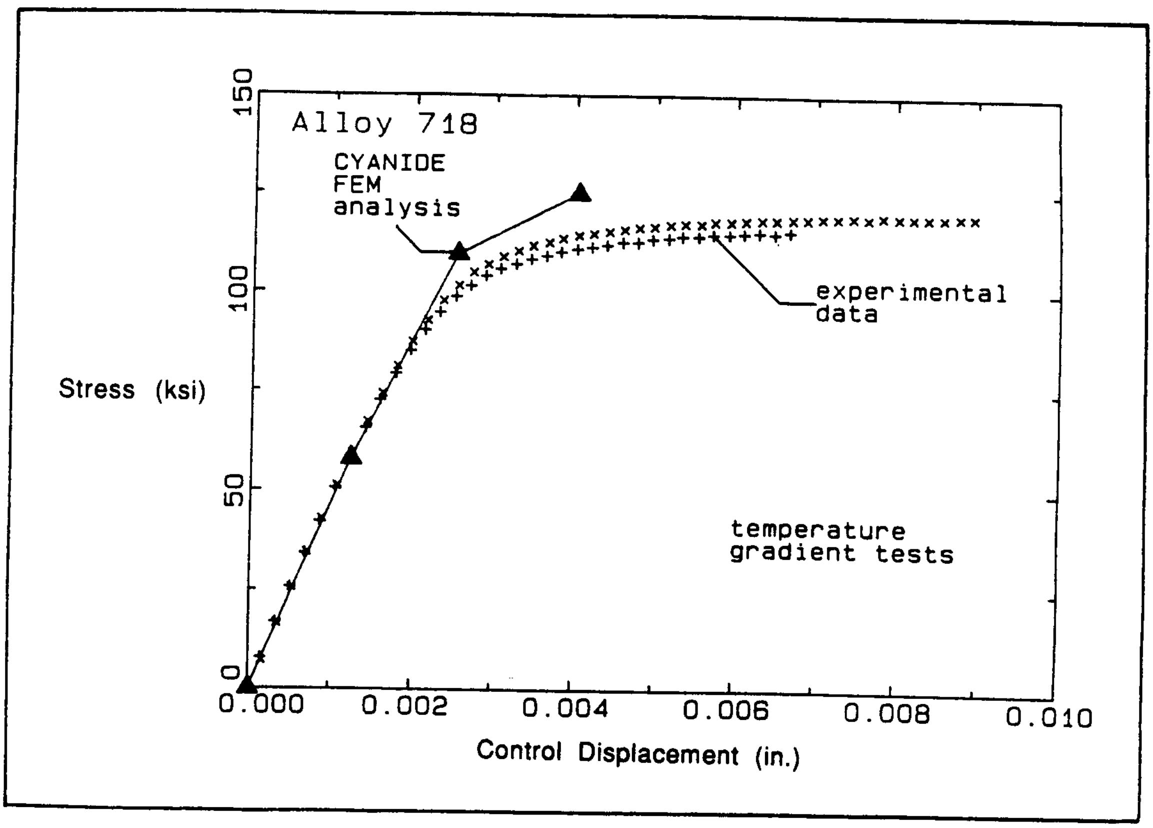

Figure 11. Analysis of Temperature Gradient Experiment